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PRELIMINARY INVESTIGATIONS OF JOINT SEISMIC AND ELECTROMACNETIC METHODS FOR NUCLEAR TEST MONITORING

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Preliminary modeling and experimental studies have been conducted to determine the source discrimination capabilities of joint seismic and electromagnetic observations for application to nuclear test monitoring. The proposed source discriminant is based on the premise that the seismic to atmospheric acoustic pulse ratio is a measurable parameter sensitive to the source mechanism. In particular, it is suggested that underground nuclear explosions have a proportionately greater seismic to acoustic pulse ratio than do relatively shallow industrial noise sources such as conventional mining and quarry explosions.

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PRELIMINARY INVESTIGATIONS OF JOINT SEISMIC AND ELECTROMAGNETIC METHODS FOR NUCLEAR TEST MONITORING

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ABSTRACT

Preliminary modeling and experimental studies have been conducted to determine the source discrimination capabilities of joint seismic and electromagnetic observations for application to nuclear test monitoring. The proposed source discriminant is based on the premise that the seismic to atmospheric acoustic pulse ratio is a measurable parameter sensitive to the source mechanism. In particular, it is suggested that underground nuclear explosions have a proportionately greater seismic to acoustic pulse ratio than do relatively shallow industrial noise sources such as conventional mining and quarry explosions.

Remote sensing of the atmospheric acoustic pulse is proposed using methods of ionospheric monitoring. Because an atmospheric acoustic pulse amplifies as a function of altitude due to decreasing neutral pressure, such ionospheric measurement systems can be extremely sensitive detectors of ground-level acoustic disturbances. Electromagnetic monitoring of the ionosphere has a demonstrated capability to detect and characterize weak acoustic signals from underground and ground-level sources. As the amplified acoustic pulse transits the ionosphere, neutral collisional coupling to the background free electrons, upon which radio wave propagation depends, transfers the acoustic disturbance into characteristic amplitude and phase disturbances in the electromagnetic signal. The specific proposed measurement method relies upon determining the amplitude and phase of a high-frequency (3-10 MHz) radio wave reflected from the ionosphere in a bistatic transmitter/receiver system. Several frequencies can be monitored simultaneously to provide multiple reflection height diagnostics, and signals transmitted from different transmitter locations can be monitored continuously at each receiver site. The combined system provides an acoustic-sensitive network of interconnected radio wave paths complementing a similar ground-based seismic monitoring network.

A preliminary joint measurement program is being initiated to determine the sensitivity and optimal instrument configuration for the proposed ionospheric observations. Since the ionospheric monitoring system is most sensitive to acoustic wave effects near the radio wave ionospheric reflection point, which occurs near the transmitter/receiver mid-point, the ionospheric monitoring sites do not have to be located close to the signal source. Small ground-level explosions have been easily detected on radio wave paths for transmitter/receiver sites several hundred kilometers from the source. Additional joint seismic and electromagnetic observations of both underground nuclear explosions and a variety of industrial noise sources are planned.

OBJECTIVE

Seismic measurements at regional distances are acknowledged to be the primary monitoring technology for verification of a low-yield threshold test ban treaty or a comprehensive test ban. Significant attention therefore is being given to the refinement of methodologies for seismic data acquisition, reduction, and interpretation so as to maximize the associated signal detection and source discrimination capabilities. Similarly, several other geophysical monitoring approaches, with limited application as primary verification technologies, are being investigated as complements to seismic measurements. In particular, the present project initiates theoretical modeling and exploratory development studies to determine the feasibility of exploiting ionospheric radio observations of atmospheric acoustic disturbances associated with ground-level explosions. These measurements are then coordinated with regional seismic observations to determine the ratio E_A/E_S of amplitudes of the atmospheric acoustic signals to the surface seismic signals. This result can in turn be used to estimate source magnitude, time history, and depth of burial, with subsequent opportunities for enhanced source discrimination. Preliminary results suggest that this approach may significantly reduce source ambiguities for small underground nuclear explosions, near-surface industrial noise such as conventional explosions, and geophysical phenomena such as small earthquakes.

The goals of the present program are to conduct simulation modeling of the atmospheric acoustic signal generation and propagation process, and to construct an experimental measurement system for exploratory research studies in conjunction with seismic measurements. Coordinated observations are planned for a variety of source events. It is the longer-range goal of these studies to assess the feasibility of ionospheric monitoring as a complementary verification technology and, if reasonable, to demonstrate the capability of this joint seismic/acoustic approach to contribute to source identification and discrimination analyses.

RESEARCH

Background. It has long been recognized that ground-level explosions generate large atmospheric acoustic disturbances that propagate to ionospheric heights and are subsequently detectable by a number of radio-frequency remote sensing techniques. Indeed, atmospheric nuclear explosions provided large acoustic signal sources that became the experimental standard for early work in this field, with associated acoustic-gravity waves in the upper atmosphere detected around the world (c.e. Hines, 1967). Subsequently, improved measurement instrumentation led to the study of ionospheric disturbances from smaller ground-level explosive sources. Observations of ionospheric response to low-level ground-based sources have become relatively routine, including studies using sources of conventional explosives (Barry et al., 1966; Simons et al., 1981), rocket launches (Duncan and Behnke, 1980); earthquakes (Davies and Baker, 1965; Wolcott et al., 1984), and volcanic eruptions (Roberts et al., 1982). The physics associated with the propagation and detection of these disturbances is relatively well understood.

The neutral acoustic wave that traverses the ionosphere as a result of ground motion can be easily calculated. In general, the amplification associated with decreasing neutral pressure with height can be calculated based upon the transformation (Pierce and Thomas, 1969) of relative overpressure, $\delta p/p$, as a conservative plane acoustic wave propagates to different altitudes. Then

$$(\delta p/p)_h = (p_o/p_h)^{1/2} \times (\delta p/p)_o$$

This acoustic amplification factor is presented in Fig.1. Typically this results in an ionospheric signal of the order of 5×10^4 times larger than the intensity of the initial ground-level disturbance. The neutral wave then collisionally couples to free electrons in the height range of 100-400 km, producing a perturbation in the ambient electron density that can be detected by a variety of radio-frequency diagnostic techniques. A number of detection methods can be employed, including high-frequency (HF) bistatic phase sounding; Faraday rotation and dual-frequency dispersion measurements of the integrated total electron content; *in situ* measurements; incoherent scatter radar observations; and satellite remote-sensing observations.

The approach providing the greatest sensitivity for the detection of small acoustic disturbances in the ionosphere is the technique of HF bistatic phase sounding. In this method, a transmitting station radiates weak (< 1 kW) continuous wave HF signals at several discrete frequencies. At a separate ground station, narrowband HF receivers are tuned to these specific frequencies, monitoring the amplitude and phase of the received signal. The purpose of a bistatic two-station set-up is to eliminate direct ground-wave radiation from the transmitter (which would mask perturbations in the ionospherically reflected signal) and to allow remote sensing overhead of regions not directly accessible to ground-based instruments (the diagnosed region is approximately at the mid-point of the transmitter-receiver path). Several frequencies are monitored simultaneously to ensure that several ionospheric reflection heights are measured and that observations are maintained through diurnal and seasonal ionospheric fluctuations. As an estimate of the sensitivity of this technique, we note that relative phase changes can easily be measured to a precision of about 0.01 radian, which at typical HF wavelengths of 50 m corresponds to a sensitivity to height variations in the wave reflection altitude of about 0.1 m. In comparison, explosions of interest for the proposed program are at a level of 0.1 kT, producing typical ionospheric disturbances of about 0.1%, or corresponding height fluctuations of about 100 m. Disturbances of this magnitude are commonly detected in association with even weak ground-level explosive sources. Therefore the problem becomes more one of understanding and interpreting the ionospheric signature of such disturbances, and not one of sensitivity of detection.

We also can compare quantitatively this approach to other alternatives. The fractional pressure excursion $(\delta p/p)_h$ can be estimated for the expected ionospheric detection altitudes and a signal reflection height perturbation of 100 m. The electron density relative perturbation $\delta n/n$ responsible for this height displacement is given by

$$\delta n/n = \delta z/H$$

where the ionospheric scale height H is typically on the order of 25 km, yielding for our example $\delta n/n = 4 \times 10^{-3}$. Using the adiabatic law and allowing for geomagnetic control of plasma motions at ionospheric heights, the neutral-gas overpressure can be estimated to be approximately $(\delta p/p)_n = 5 \times 10^{-2}$. Extrapolating back to the ground using the above amplification factor, the corresonding source ground-level relative overpressure is estimated to be $(\delta p/p)_o = 10^{-6}$. The corresponding absolute fluctuation level amplitude would be 1 microbar, or about an order of magnitude below typical background levels as measured at ground-level by microbarography. We also note that the propsed measurement technique has a systematic measurement sensitivity two to three orders of magnitude greater than the 100-m displacement example used in this example analysis.

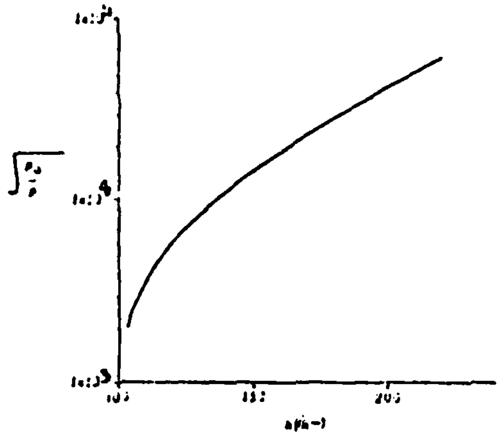

Figure 1. Acoustic amplification factor - relative overpressure versus altitude.

An acoustic wave launched by a ground-level explosion is a sensitive function of the explosion geometry and surface structures. Near-surface explosions couple more strongly, and retain a broader spectral content. The general shape of the explosion-driven disturbance assumes the form in the ionosphere of a compressional wave front followed by a rarefaction. Typical wave refraction spatial scaling is shown in Fig. 2. The acoustic wave then shows up in the HF phase as an easily recognized 'N-wave' Doppler signature. A typical observational signature is presented in Fig. 3, measured as part of a large HE explosion experiment at White Sands, NM (Simons et al., 1981). To achieve this result, post-processing included signal filtering and noise suppresion, and phase detrending to remove natural ionospheric variability acting on longer time constants.

The measurement and characterization of the acoustic wave in the ionosphere offers reasonable opportunity to characterize the ground-level source function, thereby discriminating near-surface chemical explosions from nuclear explosions at somewhat greater depth and differing spectral composition. Because the ionosphere is subject to acoustic disturbances from many other sources as well, ionospheric monitoring must perform in a relatively noisy operational environment and is not well-suited for independent test detection applications. Instead, the current research is motivated by the potential of ionospheric monitoring to address source discrimination issues as a complement to primary seismic monitoring activities.

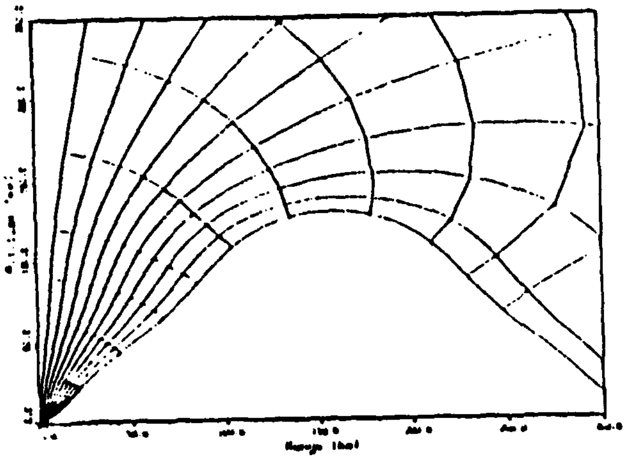

Figure 2. Typical acoustic wave refraction during atmospheric propagation.

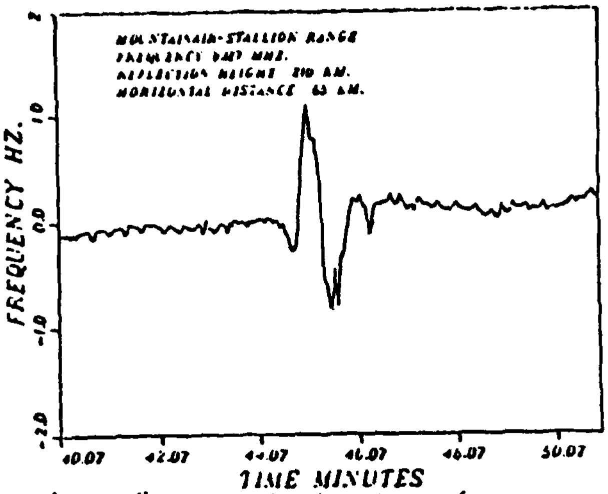

Figure 3. HF Doppler radio acoustic signature of atmospheric disturbance generated by a ground-level explosion.

Concept. The coordinated seismic and ionospheric radio acoustic observations are intended to exploit the discriminant relationship of source amplitude, signal time history, and depth of event to assist in distinguishing underground nuclear explosions from other natural and man-made signature sources. Theoretical modeling and computer simulations suggest that the E_A/E_S ratio can be used to help infer source magnitude and temporal characteristics, and depth of burial. In general, atmospheric acoustic signatures are expected to be relatively larger than associated seismic signals for sources at or near the surface, such as industrial explosions, and correspondingly smaller for events at greater depth and less efficient ground-air coupling. Similarly the time history of the ionospheric radio acoustic disturbance provides additional information on the temporal and spatial coherence of the initial source function, complementing seismic analyses seeking source discriminates based upon signal frequency content. These analyses often must make some hypotheses regarding the source, such as assuming multiple "ripple fire" detonations in conventional mining explosions. Coordinated ionospheric radio acoustic observations may assist in validating these assumptions.

Approach. Preliminary computer simulation studies incorporate models of source disturbance, ground-air coupling, acoustic disturbance propagation through the atmosphere, and subsequent radio acoustic detection and analysis. Results of one such modeling study is presented at this meeting by Archambeau, "Modeling Seismic and Atmospheric Wave Fields Generated by Near Surface Sources."

The experimental program presently involves the design and construction of a flexible ionospheric radio acoustic monitoring network. This system will be comprised of three dual-frequency transmitting stations and two receiver stations, operated so as to provide twelve independent radio acoustic data sets (six independent locations at the propagation path mid-points, and two altitudes corresponding to the two discrete radio frequencies broadcast by each transmitter). The transmitting stations consist of a crystal frequency standard, driver amplifier, 500-W final amplifier, power supply, and 4-20 MHz simple dipole antenna. The receiving stations consist of radio receivers, tunable using a 0.1 to 40 MHz frequency synthesizer, a computer-controlled digitizer and data recorder, power supply, and a 4-20 MHz delta antenna. The analog-to-digital conversion and initial data storage is achieved using an AT PC, with 100-300 Mbyte disk, and a Metrabyte card providing 16-channel, 12-bit resolution, and a digitization speed of 50,000 channels per second. After temporary real-time data accumulation in the AT hard disk, data is transferred and archived on digital tape cassettes.

At present the planned experimental instrumentation is progressing satisfactorily in its development, testing, and systems integration. Minor adjustments are being made to the system so as to be functionally compatible with earlier prototype systems constructed and currently operated by Los Alamos National Laboratory. It also should be noted that the system under development, while not requiring wholesale redesign of equipment previously fielded by us and other investigators, does represent the first attempt to make such measurements in conjunction with seismic measurements for the purpose of coordinated data analysis and interpretation. This requires additional attention to data synchronization, and pre-recording and post-experimental analysis.

RECOMMENDATIONS

It is premature to judge whether or not the approach under investigation will contribute significantly to improved source discrimination in the monitoring of underground nuclear explosions. It represents a novel approach of combining seismic and ionospheric measurements in a comparative analysis of signal observables, with subsequent attempts then to infer characteristics of the responsible source mechanism. Theoretical analysis of the radio acoustic technique, validated by experimental measurements of many man-made and natural atmospheric disturbances, argues strongly that the proposed measurement technique is several orders of magnitude more sensitive then ground-level microbarography. Preliminary computer modeling studies confirm the fundamental potential of the approach, although substantial additional modeling work remains in order to accurately interpret the observational results. Development and field testing of the necessary radio acoustic instrumentation is progressing, with field deployments scheduled to begin in the coming year.

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